FINAL PROJECT REPORT **WTFRC Project Number: AP-12-104156**

Project Title: Development of apple bloom phenology and fruit growth models

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Total Project Request: **Year 1:** $70,000 **Year 2:** $82,500 **Year 3:** $85,000

Other funding sources

Indirect support through the existing infrastructure of AgWeatherNet and its network of 158 weather stations

WTFRC Collaborative expenses:

Item	2012	2013	2014
Salaries	3,000	3,500	4,000
Benefits	1,200	1,400	1,600
Wages[1]	7,500	7,500	7,500
Benefits			
RCA Room Rental			
Shipping			
Supplies			
Travel[2]	2,400	2,700	3,000
Plot Fees			
Miscellaneous			
Total	$14,100	$15,100	$16,100

Footnotes:
[1] Labor calculated as 2 persons at $16.00/hr working 12 hrs per week for 13 weeks during the growth season.
[2] In-state travel to research plots

Budget

Organization Name: ARC-WSU **Contract Administrator:** Carrie Johnston
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Item	2012	2013	2014
Salaries	53,936	65,536	67,496
Benefits	12,564	13,464	14,004
Wages			
Benefits			
Equipment			
Supplies	1,000	1,000	1,000
Travel	2,500	2,500	2,500
Plot Fees	0	0	0
Miscellaneous	0	0	0
Total	$70,000	$82,500	$85,000

Footnotes: The budget that is requested through this proposal includes partial support for an Assistant Research Professor (Dr. Melba Salazar) who will be responsible for the overall evaluation and implementation of the various growing degree models that are applicable for conditions in the Pacific Northwest and partial support for an Application Programmer (Sean Hill) for integration of the model on the web portal of AgWeatherNet (www.weather.wsu.edu). We also have budgeted for a Graduate Student (to be hired) who will be responsible for the development of a physiological fruit growth model. The proposal includes a request for a computer for the graduate student during the first year of the project. Additional budget items include operating expenses for computer software and related costs and travel to participate in field data collection. Finally, this proposal includes support for Professor Dasgupta in the Department of Statistics to complete her statistical model development and evaluation (objective 2).

OBJECTIVES

1. Continue data collection on bloom phenology and fruit growth for selected sites and cultivars to enhance model accuracy and vigor. (Schmidt in collaboration with Castillo)
2. Continue refinement of statistical models for bloom phenology and fruit growth. (Dasgupta)
3. Develop physiological-based models for bloom phenology and fruit growth of apples. (Hoogenboom, Salazar)
4. Implement and evaluate models as decision support aids on the AgWeatherNet portal using industry beta-testers. (Hoogenboom, Salazar and Dasgupta in collaboration with Lewis)
5. Improve model/portal user interface based on feedback from beta-testers and other stakeholders. (Hoogenboom, Salazar in collaboration with Lewis)

SIGNIFICANT FINDINGS

- Differences among locations and among cultivars for the different duration of the phenological stages where found in terms of Growing Degree Days.
- An overlap of consecutive phonological stages was found for each location, year and cultivar.
- A phenological mathematical modeling approach using the duration of each stage in terms of Growing Degree Days was proposed.
- A statistical model was developed to predict final fruit size based on observational data.
- Fruit growth was modeled mathematically using Growing Degree Days. Differences among cultivars were found for each location.
- Red Delicious and Gala had significantly larger diameters than Cripps Pink. Final fruit varied from year to year and location to location.

METHODS

1. Data collection

For the development of robust models, high quality data were collected for a diverse range of environments and annual weather conditions. WTFRC staff collected bloom phenology and fruit growth data from established sites to augment data sets from the previous project.

2. Continue refinement of statistical models for bloom phenology and fruit growth

For the bloom models, data were compiled for 2010 and an ordinal logit model was used to fit the data. All data for phenology, growth and temperature were compiled for 2011 through 2013. For the growth models, data for 2010 through 2013 were combined and new parameters were estimated. For the bloom model similar procedures were followed. Following a successful development of both the statistical bloom phenology model and the statistical fruit growth model, they were evaluated with the data that were collected during the 2012 and 2013 growing seasons.

3. *Develop physiological models for bloom phenology and fruit growth*

An analysis was performed for phenological data recorded at regular intervals for Gala, Red Delicious and Cripps Pink during the 2010, 2011, 2012 and 2013 growing seasons for 10 locations from bud break until full bloom in order to identify the dynamics of each phenological stage.

A descriptive analysis was conducted and trends were calculated for each phenological event as well as the duration for each year and location. Physiological time was used as input of the model for the different phenological stages for apple, referred to as Growing Degree Days (GDD) or Thermal time. The requirements for the different phenological stages of the most important apple cultivars using daily temperature records from the AgWeatherNet were summarized.

The phenological model was based on the duration of each stage in terms of GDD for a threshold temperature Tb = 43°F. The lower limit or beginning of a stage was determined as: Lower limit = $\sum_{i=1}^{10}\sum_{j=1}^{3} Min(GDD_{ij})/n$ and upper limit or the end of a stage was calculated as: Upper limit =$\sum_{i=1}^{10}\sum_{j=1}^{3} Max(GDD_{ij})/n$, where i = 1, 2, .., 10 are the locations and j = 1, 2, 3 the years 2011, 2012 and 2013. The data collected in 2010 and 2014 were used for model evaluation.

The performance of the model was compared using the weather data collected with the Hobo data loggers that were part of the data collected by WTFRC. To identify if there were significant differences between locations, a procedure GLIMMIX of SAS9.3 was used. The categorical variable stage was the dependent variable and was linked to a multinomial distribution.

The diameter of 50 apples of every cultivar in each location was measured weekly for each year. As a function of the GDD, a growth diameter mathematical model was proposed; the rate of the diameter growth was an exponential function derived from the Von Bertalanfy growth curve of the diameter:

$$\partial D = ake^{-kGDD}$$

Where D is the apple diameter, *a* is the upper asymptote (maximum diameter) and *k* is a shape parameter of the curve.

To simulate the diameter for each day *t*, an Euler method was used:

$$Diameter_t = Diameter_{t-1} + \partial D\Delta t$$

Where Δt is the time step equal to one day. Thus the estimation of the apple diameter for the day t depends on the day t-1 plus the rate of growth time the time step. An evaluation is planned to determine the most accurate growth model. Data collected in 2010 and 2014 will be used for model evaluation.

4. Implement and evaluate models as decision support aids on the AgWeatherNet portal

To assist the growers for making decisions, an information delivery system and media tool will be posted in the web page using the models developed. This tool will provide, in an easy and user-friendly way, thermal time in real-time (current) for different environmental conditions where local weather data are available through tables and graphs as well as information about the current phenological and development stages and the climatic requirements to complete the next stage as well as the current apple diameter. The system will be available through a link created on the AgWeatherNet web portal and other web portals where information for apples is provided

5. Improve model/portal user interface and release for general use

The overall goal is to develop a web portal that will provide a guideline and advisory for the growers who are monitoring their individual apple orchards in terms of weather conditions and weather predictions. That will ultimately allow for better planning to improve fruit quality, increase yield, more efficient marketing and ultimately result in an increase in net returns. We will work closely with WSU Extension and industry representatives as beta testers. We will try to incorporate all comments to help improve the tool and decision aid to the benefit of the local apple growers.

RESULTS & DISCUSSION

1. Data collection

Observations of bloom phenology were recorded from 2010 to 2014 by WTFRC internal staff every Monday, Wednesday, and Friday in 29 blocks clustered around 10 location nodes. Current varieties include Red Delicious, Cripps Pink and Gala. WTFRC staff also collected fruit size data starting at petal fall until final harvest with a brief break during thinning.

2. Continue refinement of statistical models for bloom phenology and fruit growth
In 2014 we focused on developing a predictive model for the growth data. Based on previous work we found that the weather and location related variables played an important role in the prediction of diameter close to harvest. We observed that the date of Full Bloom (FB) was a good proxy variable for the weather variables (high R-square when regressing weather variables on FB). Hence we tried to do our predictive model with predictors FB and days after full bloom (DAFB) to account for location and year. The model for Gala is shown here as an example. It is a mixture of the Richard's curve and a linear model given as:

$$y = \frac{\beta_0}{(1 + \exp(-\beta_1\,(DAFB - \beta_2\,)} + \beta_3\,FB + \beta_4\,M_{40} + \ \beta_5\,M_{50} + \ \beta_6\,M_{60} + \ \beta_7\,M_{70} + \ \beta_8\,M_{80}$$

where y represents the predicted mean diameter at day 100, M40, M50, M60, M70, M80 represent mean diameter at day 40, 50, 60, 70, 80 respectively. Hence size at a particular time point was predicted using past data and the mean of diameter 20 days before the date we are predicting. An initial implementation of the model is discussed in section 4 below.

3. Develop physiological models for bloom phenology and fruit growth
The percentage of buds for each phenological stage was determined for each sampling date, year, location and cultivar. Differences in the phenological stages distribution through time by cultivar year, and location were observed i.e. the duration of the stages for Cripps Pink, Gala and Red Delicious were not the same through the years and location. Thus the starting and final day of each stage varied among cultivars, years and localities. As a result there was an overlap of the consecutive stages (Fig. 1). There was significant effect for year, cultivar, location and their interactions as an indication of the dependence among factors. In other words, the pattern of the stage distribution for years depended on cultivar, year and location.

The trend of the distribution for each phenological stage was determined for each cultivar and each location. An example for Gala for each stage is presented for 2010 -2013 for blocks located in Brays Landing, Chelan, Prosser and Royal (Fig. 2). The dynamics of the different phenological stages were analyzed using Growing Degree Days (GDD). The base temperature for heat accumulation was 43 ºF for each location and each cultivar for the 2011, 2012 and 2013 growing season. The analysis showed different durations among locations and among cultivars for the different phenological stages (Table 2). Gala was the cultivar that started and ended later than Cripps Pink and Red Delicious and the duration depended on the cultivar and stage (Figure 3). More than 70% of the variability in the duration of the stages duration was explained by the model; the error (RMSE) varied from 40 to 56 DGG and the coefficient of variation from 23 to 25%

For all locations Red Delicious and Gala had significantly larger diameters than Cripps Pink. The final size of the fruit varied from year to year and location to location. Cultivar differences in fruit diameter reflected differences in mean fruit diameter as well as fruit growth period (Fig 4). The proposed model estimates the apple diameter as functions of the GDD. If local weather data are available from a meteorological station the model can provide an estimate for fruit size diameter without having to take samples from the field.

4 Implement and evaluate models as decision support aids on the AgWeatherNet portal
During the final year of the project the initial models were implemented on the AgWeatherNet portal for in-house testing only. An example of the phenology model is shown in Figure 5. Further

development in cooperation with stakeholders is required with expected Beta testing during the 2015 growing season.

An initial version of the model developed under Objective 2 is shown in Figure 6. Based on the observed bloom data and measured early fruit diameter the model provides a projection of fruit diameter change as the fruit grows and final fruit diameter. The different lines in the figure depict the different model parameters that are used during the growing season. Inputs for this model are local measurements only and are not site dependent.

5 *Improve model/portal user interface and release for general use*

Due to the delay in the development of the models for implementation on the AgWeatherNet portal, the models were not released to the general public.

Table 1. Locations and associated elevation for each orchard and cultivars sampled.

Location	Elevation (ft)
Brays Landing	900 (RD,CP,G)*
Chelan	1120 (CP), 1450 (RD,G)
East Wenatchee	910 (RD, CP), 1025 (G)
Konnowac Pass	870 (RD,CP,G)
Naches	1580 (RD,G)
Omak	1250 (RD,G)
Prosser	681 (RD,CP,G)
Royal City	1095 (CP), 1055 (RD,G)
Orondo	755 (RD,CP,G)
Sunrise Orchards	910 (RD), 880 (G), 775 (CP)
Wapato	879 (RD,CP,G)

* RD = Red Delicious, CP = Cripps Pink, G = Gala

Table 2. Degree days for the start and end of each stage and the standard deviation for Cripps Pink, Gala and Red Delicious.

Cultivar	Stage	Stage Start GDD	Stage End GDD	Standard Deviation of the Start	Standard Deviation of the End
Cripps Pink	A	34.81	71.81	16.48	20.78
Cripps Pink	B	48.53	106.28	14.23	24.23
Cripps Pink	C	90.07	149.24	21.17	35.26
Cripps Pink	D	117.21	170.49	24.70	38.37
Cripps Pink	E	148.26	224.14	30.91	44.36
Cripps Pink	F	187.42	255.90	37.55	48.42
Cripps Pink	G	216.72	326.19	48.02	52.49
Cripps Pink	H	262.71	332.98	57.89	77.51
Gala	A	35.47	84.28	15.88	26.96
Gala	B	58.31	122.51	18.44	34.42
Gala	C	111.23	175.38	24.38	48.12
Gala	D	148.29	205.14	29.48	45.59
Gala	E	182.63	246.28	40.02	52.89
Gala	F	220.95	273.88	45.59	53.52
Gala	G	243.19	328.51	50.22	70.90
Gala	H	297.69	365.39	51.55	80.94
Red Delicious	A	37.32	87.61	14.84	28.15
Red Delicious	B	59.33	122.94	17.87	30.27
Red Delicious	C	112.13	177.01	25.88	53.15
Red Delicious	D	142.41	201.44	28.99	46.62
Red Delicious	E	171.14	243.67	41.34	50.43
Red Delicious	F	207.00	266.50	43.53	54.78
Red Delicious	G	234.47	332.74	46.67	76.68
Red Delicious	H	291.06	360.55	53.95	85.25

A = Green Tip; B = ½ inch green; C= Tight Cluster; D = First Pink; E = Full Pink; F = First Bloom; G = Full Bloom; H = Petal Fall

Table 3. Evaluation of the phenological model based on Growing Degree Days.

Cultivar	RMSE (GDD)	R^2 (%)	CV (%)
Cripps Pink	40.60	82.82	23.76
Gala	46.39	79.78	24.20
Red Delicious	55.21	72.18	24.79

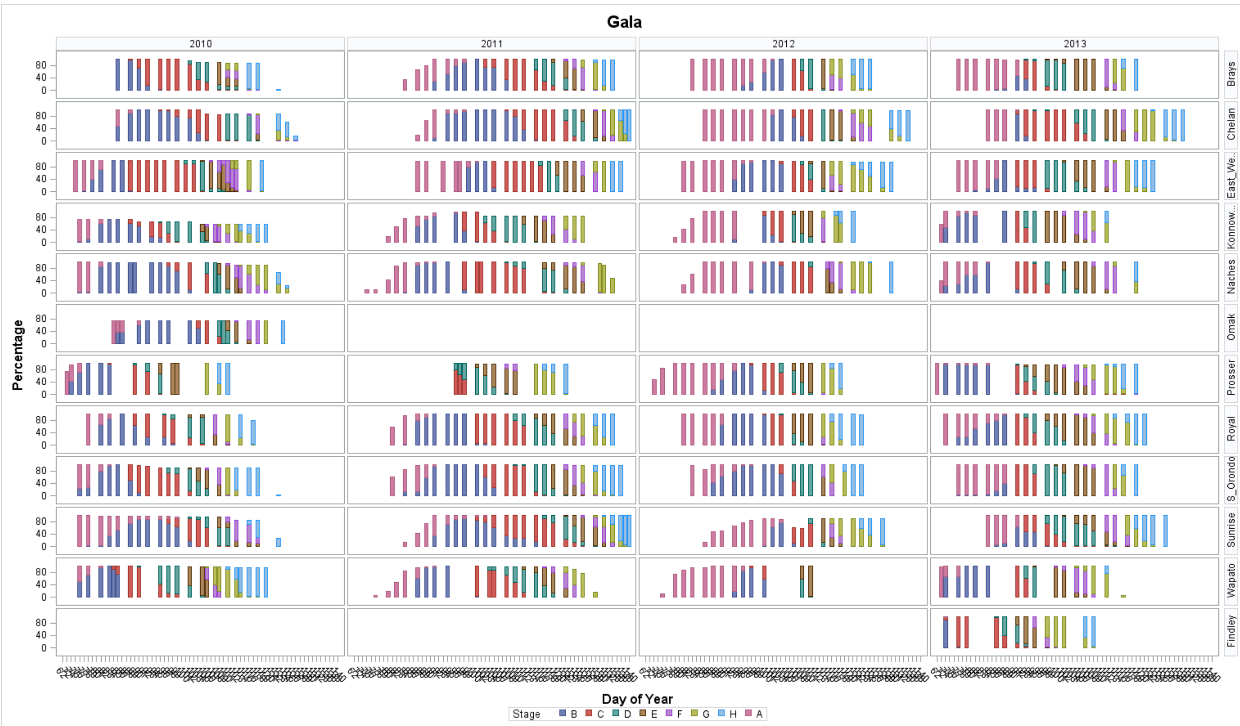

Figure 1. Phenological stage distribution for each sampling date for Gala for 2010 through 2014 (columns) for each location (rows). Each color represents a different phenological/growth stage; see Table 2 for Growth Stage Definitions.

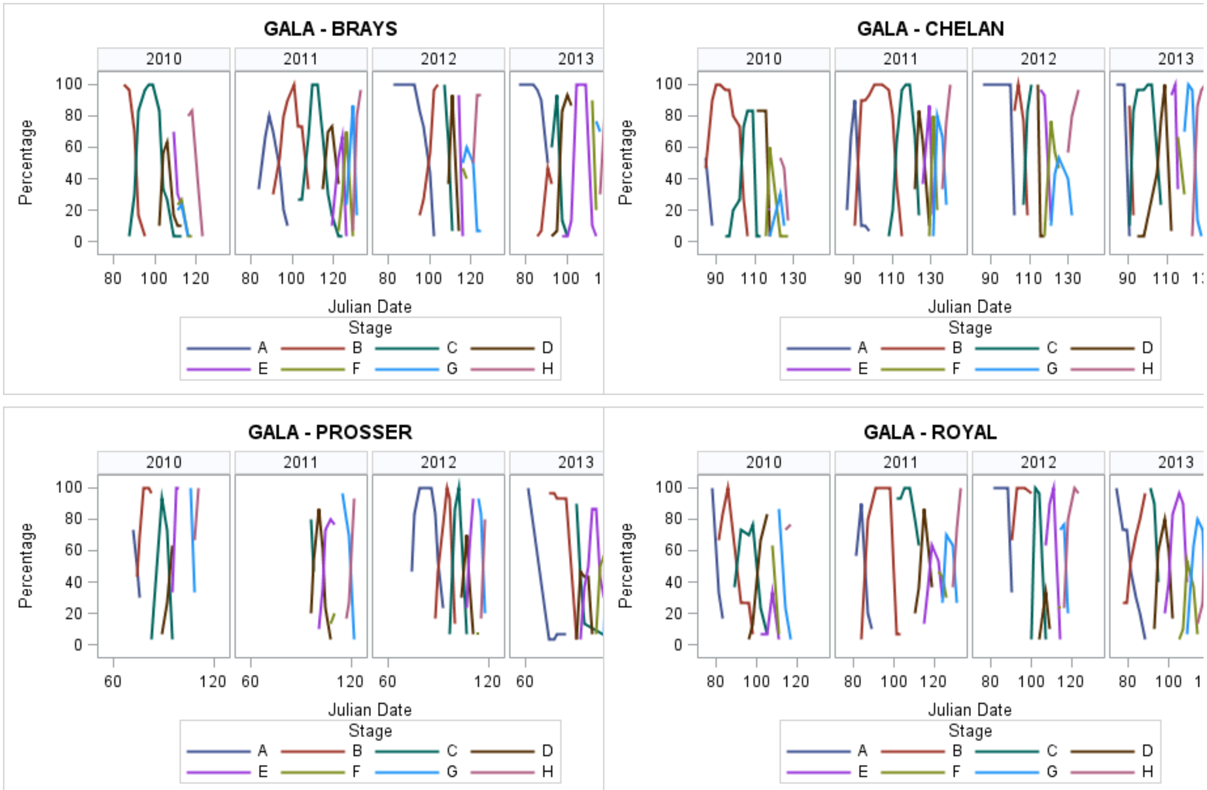

Figure 2. Trend of the distribution for each phenological stage for Gala for four study locations (Brays Landing, Chelan, Prosser, and Royal City). See Table 2 for growth stage definitions.

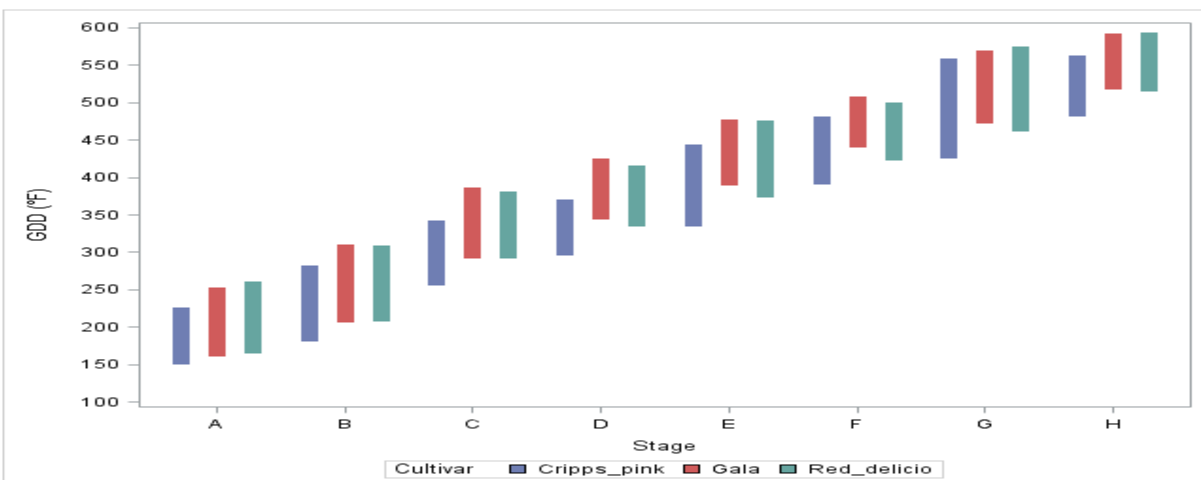

Figure 3. Duration of the phenological stages for Cripps Pink, Gala and Red Delicious. See Table 2 for growth stage definitions.

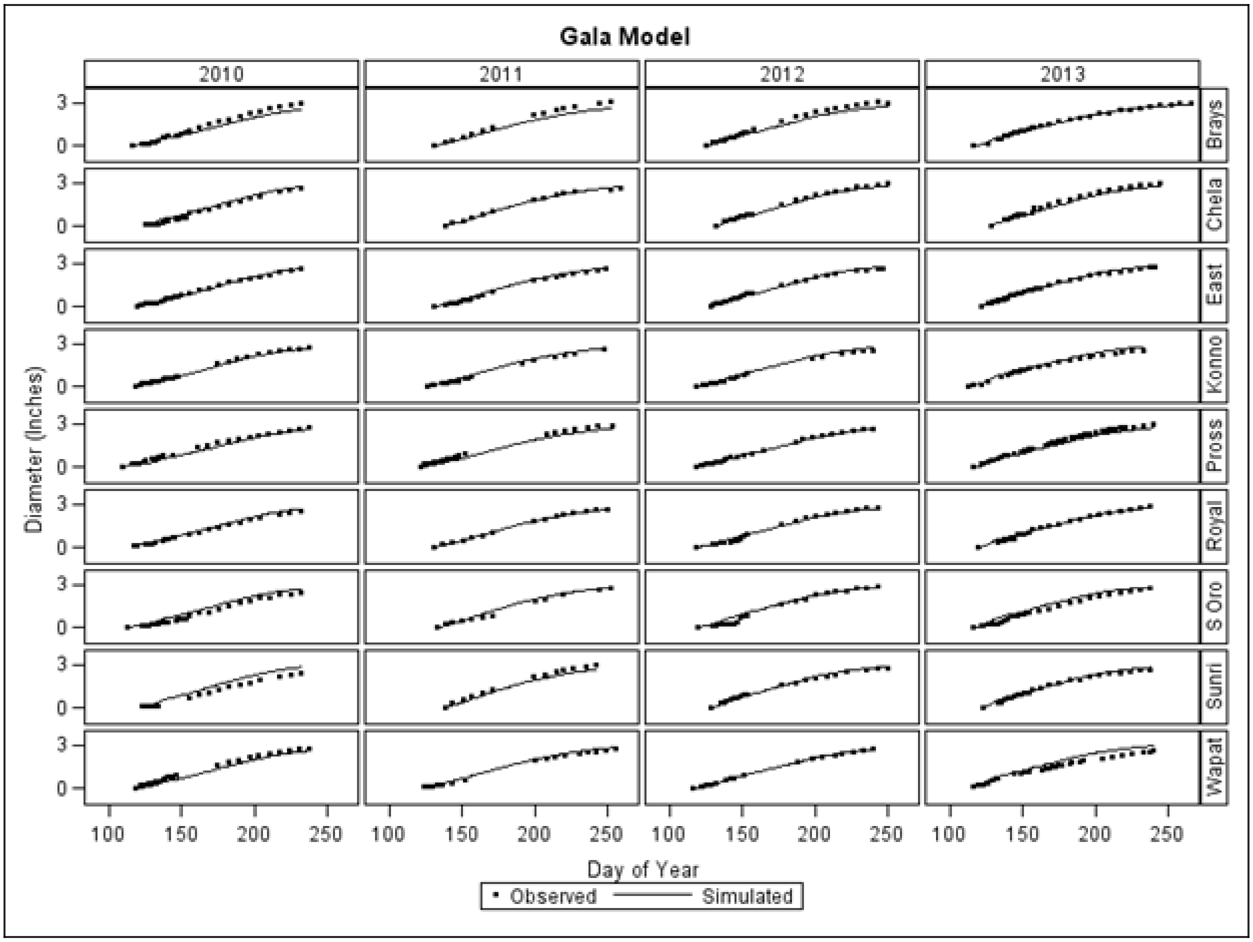

Figure 4. Observed and estimated diameter for each cultivar, year and location for Gala.

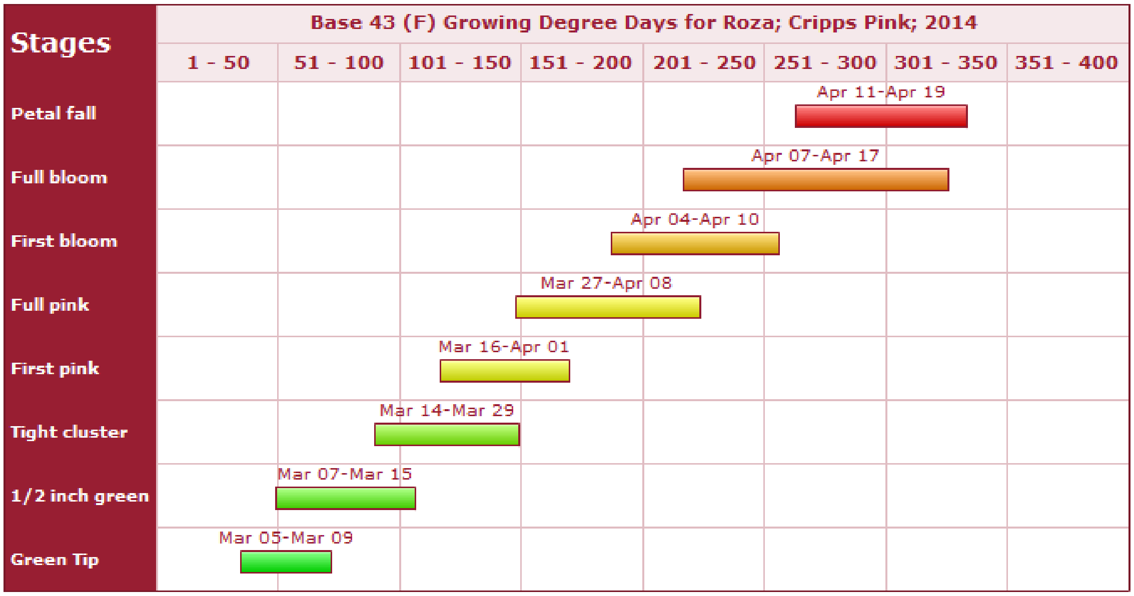

Figure 5. Example of the interface for the phenological model for Cripps Pink for 2014 based on weather data from the Roza farm at Prosser as implemented on the AgWeatherNet portal.

Figure 6. A prototype example of the statistical diameter prediction model.

EXECUTIVE SUMMARY
The overall goal of this project is to be able to predict bloom phenology and final fruit size of apples. During the first phase of the project from 2009 through 2011 protocols were established to measure apple bloom phenology, starting at green tip until petal fall as well as non-destructive measurements of fruit size. Data were collected for Red Delicious, Cripps Pink, and Gala for 11 locations. During the second phase of the project from 2012 through 2014 data collection was continued, while at the same time a range of modeling approaches was tested to determine the relationship between apple bloom phenology and local weather conditions as well as fruit diameter. A simple Growing Degree Day model has been developed using a base temperature of 43 F that can predict the beginning and ending for all eight successive apple stages based on local weather conditions. Two fruit diameter models were also developed. One is based on local measurements and can provide a prediction for final fruit diameter. The second model predicts the actual average fruit size based on local weather conditions. Initial versions of all models have been implemented for demonstration on the AgWeatherNet portal and were demonstrated to a select group of stakeholders during a meeting held in Prosser in October, 2014. Further work is needed for testing of all models, possibly with an integration of both fruit size models as a combined hybrid model. The interface for the models on the AgWeatherNet portal will be shared with a select group of growers for initial evaluation and improvement, followed by release to the general public. During the past six years this project has made great progress in not only understanding the impact of weather on apple development and fruit growth, but also developing sound scientific models that can be used by growers through the AgWeatherNet portal.